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Translation of "Issledovaniye vysokoskorostnykh pryamotochnykh raspylitel'nykh apparatov pri absorbtsii khorosho rastvorimykh gazov"
Possible Source: Khimicheskoye Mashinostroyeniye, No. 2, pp. 46-52

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON NOVEMBER 1965

ABSORPTION OF HIGHLY SOLUBLE GASES BY HIGH SPEED AXIAL FLOW ATOMIZING EQUIPMENT

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Symbols

ΔP	total pressure drop in the Venturi tube in N/m^2
ΔP_t	pressure drop due to tube resistance and the dispersion of the liquid in N/m^2
ΔP_{ac}	pressure drop due to the acceleration of the gas-liquid flow due to a pressure decrease in the tube, N/m^2
ΔP_r	pressure drop due to the rise of the gas-liquid flow, N/m^2
ρ_l	liquid density, kg/m^3
ρ_g	gas density, kg/m^3
g	acceleration due to gravity, m/sec^2
H	height of Venturi tube in meters
L	liquid consumption, kg/sec
G	gas consumption, kg/sec
W_g	mass gas flow rate, $kg/(m^2 \cdot sec)$
d_{th}	throat diameter in meters
ΔP_s	pressure drop in the tube for a single phase flow, in N/m^2
μ_l	liquid viscosity, $N \cdot sec/m^2$
μ_g	gas viscosity, $N \cdot sec/m^2$
σ	surface tension, N/m

N_{og} number of transport units

V_t the actual absorption volume of the Venturi tube in m^3

m specific liquid consumption, ℓ/m^3

σ resistance coefficient

h height of the absorption volume in meters

At the present time considerable attention is being given to axial /126* flow atomizing absorbers in which the liquid is atomized by a gas moving with a high velocity (20-30 m/sec); best known are the Venturi absorbers and the atomizing absorber (AA).

Two modifications of the Venturi absorbers are known. In the absorber without a jet orifice the gas moves in the vertical Venturi tube in the upward direction, passes by the entrance to the tube over the liquid, and captures the liquid (refs. 1-4). In an absorber with a jet orifice the gas moves along the vertical Venturi tube in the downward direction and the liquid is supplied through a jet orifice which is placed near the mouth of the tube (refs. 5-10).

The AA absorber (refs. 11 and 12) is very similar to the Venturi jet orifice absorber in principle and differs only in that the liquid is supplied in the form of a film and there is no diffuser.

The above instruments have been tested for a series of absorption processes and have received some application in industry. However, they were tested under incomparable conditions. Also, not all of the relationships necessary to determine the hydraulic resistance and the coefficient of mass transfer were established.

*Numbers given in the margin indicate the pagination in the original foreign text.

Below we present the results of investigations conducted with three such instruments under identical conditions. The investigations were carried out by using a model with a throat diameter of 20 mm (some of the experiments were carried out using the Venturi instruments without a jet orifice and with a throat diameter of 34 and 48.5 mm). The experiments were conducted using /127 the ammonia-water system, which makes it possible to obtain data for the mass transfer which can be applied to other highly soluble gases. During the experiments the ammonia concentration at the output to the instrument was 0.5-1 percent by volume. The amount of ammonia in the gas before and after absorption was determined by passing a fixed volume of gas through flasks with 0.1 or 0.01 normal solutions of H_2SO_4 with subsequent titration. The ammonia content in the outflowing liquid was also determined by titration and the initial alkalinity of the water was taken into account. Air consumption was measured by means of a duplex diaphragm while water consumption was measured by a rotameter. The pressure drop in the instrument was measured with a U-type manometer. The temperature of the gas and of the liquid entering the instrument and leaving the instrument was measured with a mercury thermometer. Experiments were conducted with a gas mass velocity of 23-48 kg/(m$^2\cdot$sec) and with a specific liquid consumption of 1-6 l/m^3.

Measurement data were used to construct a material balance and the results of the experiments when the balance deviated by more than ±15 percent were not taken into account. Data from the remaining experiments were used to determine the number of transported units referred to the gas concentration. A large part of the experiments was carried out by means of a Venturi absorber without a jet orifice and with the AA absorber. A small number of experiments was carried out with the Venturi absorber equipped with a jet orifice.

Venturi Absorber Without a Jet Orifice

The resistance and mass transfer in a Venturi absorber without a jet orifice for the air-ammonia system have been studied earlier (ref. 1). In the work described here the range of air velocities was extended towards the lower v[illegible] and the effect of tube dimensions on the resistance and mass transfer was also investigated.

The schematic of the laboratory setup is shown on figure 1. Atmospheric air is pumped by the vacuum pump 5 through filter 1 and absorber 2. Ammonia from the storage tank 3 through a valve and flowmeter 8 is introduced into a supply line ahead of the mixer 4 which consists of a Venturi tube followed by a damping screen. Water from the pressure vessel 6 with a constant liquid level is supplied through the rotameter 9 to the lower part of the absorber and flows over into the drain system after it leaves its upper part.

The diameter of the absorber is approximately 300 mm; its lower part is replaceable. This makes it possible to install Venturi tubes with different throat diameters and still retain the constant ratio between the diameters of the tube and the lower part of the absorber.

The basic Venturi tube with a throat diameter of 20 mm was constructed to high tolerances; the diffuser angle was equal to 8°, the converging nozzle angle was equal to 44° (it is known that if this angle is varied within 25-45° it has practically no effect on mass transfer and resistance (ref. 1)). The large Venturi tubes were fabricated from sheet iron. Since the resistance of Venturi tubes depends on the method of fabrication and particularly on the shape of the inlet edge, a Venturi tube which had the same dimensions as the initial tube was also investigated. The dimensions of the different Venturi tubes which were tested are shown in the table. When tubes No. 1, 1a and 2 were used, a baffle

Tube No.	Diameter, mm			Length, mm		Diffuser angle	Con-verging nozzle angle	Tube
	Throat	Input cross-section	Output cross-section	Diffuser	Con-verging nozzle			
1	20	50	50	213	38	8^{o}	44^{o}	machined from steel
1a	20	49.3	49.3	215	39	$7^{o}46'$	41^{o}	welded from sheet iron
2	34	87	85.6	330	66	$8^{o}56'$	$43^{o}40'$	welded from sheet iron
3	48.5	122	124	517	93	$8^{o}20'$	43^{o}	welded from sheet iron

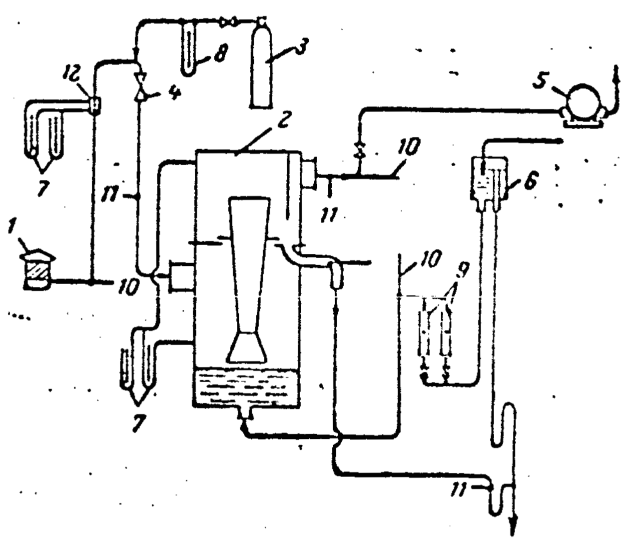

Figure 1. Laboratory setup for investigating the Venturi absorber without a jet orifice: 1, filter; 2, absorber; 3, storage tank with ammonia; 4, mixer; 5, vacuum pump; 6, pressure vessel; 7, manometer; 8, rheometer; 9, rotameters; 10, thermometer; 11, samplers; 12, diaphragm.

was installed at the exit from the absorber; when tube No. 3 was used the housing of the absorber served as the baffle.

Mass Transfer

The results of experiments carried out using Venturi tube No. 1 were in good agreement with the data mentioned above (ref. 1). Therefore, this tube was used to conduct only one series of experiments with $W_g \approx 26$ kg/(m^2·sec) within the sprinkling density limits of L/G = 0.3-4.5 kg/kg. This range of sprinkling density at the specified gas velocity corresponds to the first mode of absorber operation which has been called the pulsating mode in an earlier work (ref. 1).

The results of the experiments are shown in figure 2 which gives the variation in the number of transport units as a function of spring density. The corresponding empirical equation has the form

$$N_{og} = 1.01\ (L/G)^{0.28} \tag{1}$$

Figure 3 shows the results of experiments conducted with geometrically similar tubes of different sizes. It follows from this figure that when /128 the dimensions of the tube increase and the geometric similarity is retained the number of transported units for the same value of L/G increases while the slope of the line remains constant.

Thus the general relationship in the first mode for geometrically similar tubes has the form

$$N_{og} = A(L/G)^{0.28} \tag{2}$$

where A is a function of the characteristic dimension.

When simple coordinates (fig. 4) are used to plot the quantities A as a function of the two absorption volume V_t (the volume of the Venturi tube and of

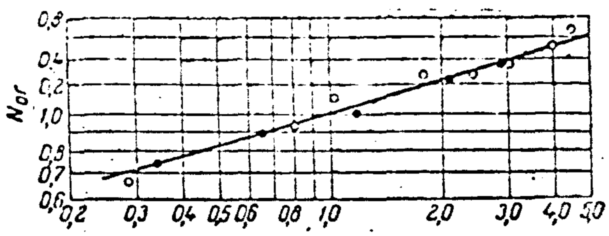

Figure 2. Variation in N_{og} as a function of L/G in the first mode for a Venturi absorber without a jet orifice when the tube has d_g = 0.02 m: o, tube No. 1; W_g, 26 kg/(m^2·sec); o, data published in the literature for a machined tube (ref. 1), W_g = 36.2 kg/(m^2·sec).

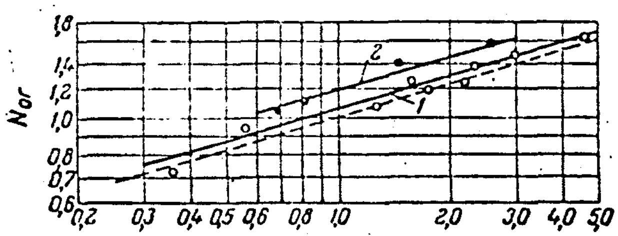

Figure 3. Variation in N_{og} as a function of L/G in the first mode for a Venturi absorber without a jet orifice (tubes with different d_g) when W_g = 26 kg/(m^2·sec) (the broken line corresponds to the straight line in figure 2): 1, tube No. 2; 2, Tube No. 3.

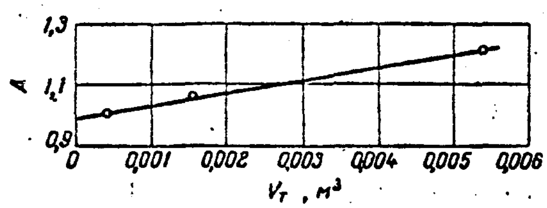

Figure 4. Variation in A as a function of V_t.

the atomizing jet above it before the reflecting partition), the points form a straight line given by the equation

$$A = 0.933 + 40.7\ V_t$$

or in the general case

$$A = A_0 + Bd^3_{th}. \tag{3}$$

The general expression for the number of transported units may be written in the form

$$N_{og} = N_0 + kV_t. \tag{4}$$

We must assume that the process of mass transfer in the Venturi tube has two stages: the mass transfer during the instant of time when spray is formed and destroyed (corresponding to the number N_0 of transported units) and mass transfer in the tube whose intensity is a function of V_t. Apparently the coefficient k is practically constant only in the narrow interval of test tube dimensions and when these are further increased it decreases as the absorption volume increases.

Resistance.

The total pressure drop in the Venturi tube consists of three parts:

$$\Delta P = \Delta P_t + \Delta P_{ac} + \Delta P_r. \tag{5}$$

The quantity ΔP_{ac} does not depend on the dimensions of the tube. When the total pressure drop is not greater than 4,000 N/m^2 it is a fraction of a percent of ΔP and can be neglected.

The quantity ΔP_r is determined by the equality

$$\Delta P_r = \left(1 + \frac{L}{G}\right) \rho_r g H \tag{6}$$

For the Venturi tubes which were investigated this quantity does not exceed 1-2 percent; however, for tubes of a larger size it may become noticeable. Therefore, the results of the experiments are processed taking into account ΔP_r.

Figure 5 presents data on the resistance of all test tubes as the variation in $\Delta P_t = \Delta P - \Delta P_r$ as a function of L/G when $W_g = 26$ kg/(m^2·sec).

The points for the tube with $d_{th} = 0.02$ m fall on parallel lines. The data obtained in the following investigation and earlier when reduced give the following relationship for machined tubes in the first mode operation

$$\Delta P_t = (0.069\, W_g^{2.2} + 300)\ (L/G)^{0.358}. \tag{7}$$

For the tube made of sheet iron and having a sharp edge the resistance is 10 percent higher and is given by the equation

$$\Delta P_t = 1.1(0.069\, W_g^{2.2} + 300)\ (L/G)^{0.358}. \tag{8}$$

We can see from the drawing that as d_{th} increases and the geometric similarity is retained, the resistance to the two phase flow in the Venturi absorber increases. /129

Earlier the following relationship was given (ref. 3) for the pressure drop in a two phase flow in vertical cylindrical tubes:

$$\frac{\Delta P_t}{\Delta P_s} = f\left(L/G, \frac{W_g^2}{g d_{th}}, \frac{\rho_\ell}{\rho_g}, \mathrm{Re}_r, \frac{\mu_e}{\mu_g}, \frac{\sigma}{g(\rho_\ell - \rho_g)d^2}, \frac{H}{d_{th}}\right) \tag{9}$$

The data of the present work could not be processed in the same manner due to the lack of precise data on the magnitude of ΔP_s. Unlike the case of a round

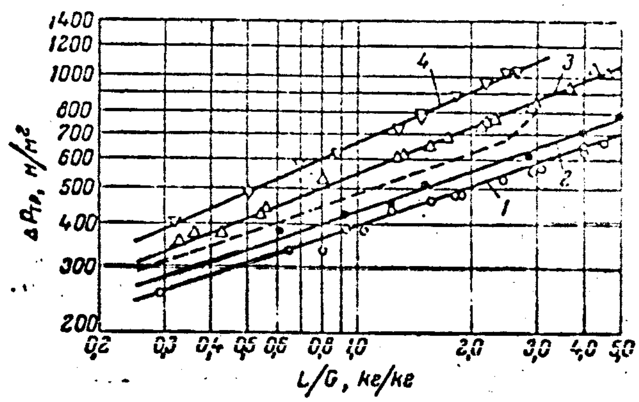

Figure 5. The resistance of a Venturi absorber without a jet orifice containing pipes with different diameters when W_g = 26 kg/(m^2·sec) (the broken line represents the published data (ref. 1), W_g = 36.2 kg/(m^2·sec)): 1, tube No. 1; 2, Tube No. 1a; 3, Tube No. 2; 4, Tube No. 3.

tube with constant cross-section, the Venturi tube absorber has a value of ΔP_s which is not equal to the resistance of the dry tube but it is somewhat higher due to the surface friction of the liquid in the lower part of the instrument. Therefore, in this case we present only an empirical equation for tubes 1a, 2 and 3 when W_g = 26 kg/(m^2·sec)

$$\Delta P_t = (270 + 8200 d_{th})(L/G)^{0.20+8.4 d_{th}} \tag{10}$$

Due to the insufficient number of points in the narrow range of d_{th} this equation cannot be extrapolated beyond the limits of test tube dimensions; however, it can be used for the hypothesis concerning the interrelation between tube dimensions and its specific resistance, i.e., resistance per unit transport.

On the basis of equations (5), (6) and (10) the expression for the total pressure drop may be written in the following general form:

$$\Delta P = (a + bd_{th})(L/G)^{p+nd_{th}} + \left(1 + \frac{L}{G}\right)\rho_g g H \qquad (11)$$

or

$$\Delta P = (a + bd_{th})(L/G)^{p+nd} + \left(1 + \frac{L}{G}\right) cd_g \qquad (12)$$

where $c = \rho_g g \frac{H}{d_{th}}$ (for geometrically similar tubes, H/d_{th} = const).

Taking into account expressions (2) and (3) derived above, we obtain

$$\Delta P/N_{og} = \frac{(a + bd_{th})(L/G)^{p+nd_{th}} + \left(1 + \frac{L}{G}\right) cd_{th}}{(A_0 + Bd_{th}^2)(L/G)^q} \qquad (13)$$

Analysis shows that as d_{th} increases, this function first increases to some maximum value and then decreases. Thus we can assume that (although the resistance of the Venturi tubes increases with dimensions when L/G and W_g are constant) the specific resistance and consequently the total resistance will be of the same order of magnitude for large tubes as for small tubes when the separation effect is the same. This hypothesis must be verified by conducting experiments with large diameter Venturi tubes even though certain data confirm it. Thus in the absorption of silicon tetrafluoride in an absorber with a Venturi tube (ref. 4) having a throat diameter of d_{th} = 185 mm, when W_g = 35.4 kg/(m^2·sec) and N_{og} = 1.5-3.5 the specific resistance including the resistance of the reflecting partition was $\Delta P/N_{og}$ = 400-600 N/m^2, i.e., it was in the same limits as the resistance in a Venturi tube with d_{th} = 20 mm.

AA Absorber

The laboratory setup and the basic dimensions on the absorber are shown in figure 6. Water enters the absorber 1 through a sprinkling device 2 with four tubes 3, which are lowered almost to the bottom of the upper part of the

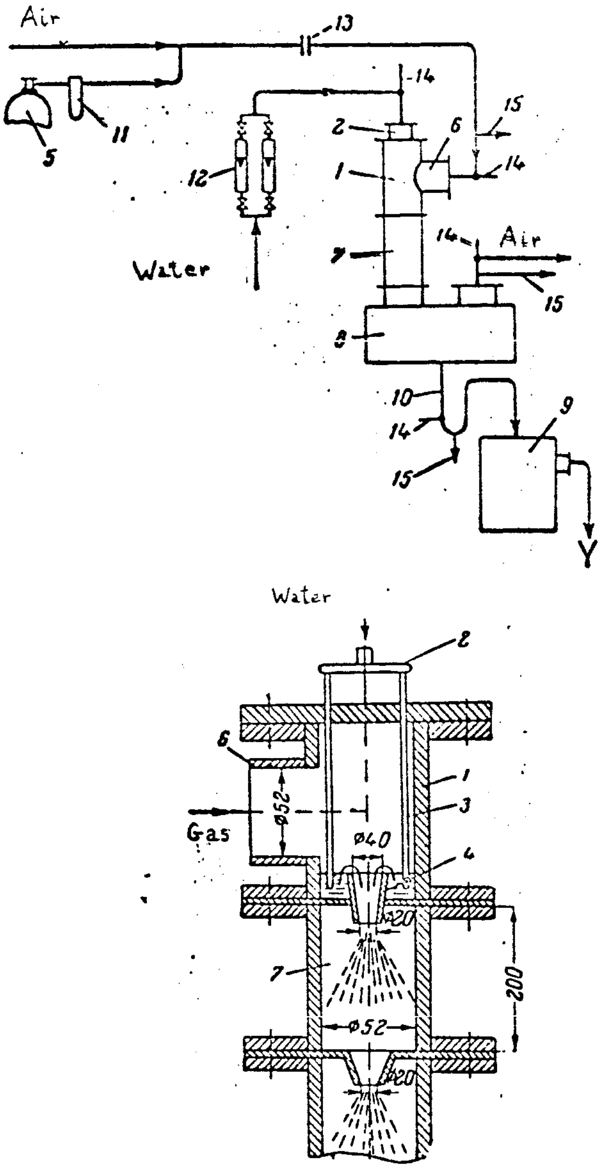

Figure 6. Laboratory set-up of the AA absorber: 1, absorber; 2, sprinkling device; 3, tubes; 4, conic attachment; 5, storage tank with ammonia; 6, connecting pipe for the air-ammonia mixture supply; 7, absorption part; 8, separator; 9, vessels for receiving the liquid; 10, hydraulic valve; 11, rheometer; 12, rotameters; 13, diaphragm; 14, thermometers; 15, test samplers.

absorber, moves up and flows over the edge of a conic attachment 4. The mixture of the air blown from the atmosphere and ammonia fed from the storage tank 5 is directed to the absorber through a connecting pipe 6. Then this mix- /130 ture passes through the conic attachment and disperses the liquid film into small droplets. The liquid-gas flow formed in this manner is fed to the absorption part of the equipment 7 where the absorption process takes place. After this the gas and the liquid are separated by the separator 8, the liquid is collected in vessel 9 where it is fed through a water seal 10.

In order to determine the effect of the absorption volume on the degree of ammonia, capture experiments were conducted with three replaceable absorption parts of the equipment having a height of 200, 400 and 600 mm.

Single step and double step AA instruments were tested. The distance between the conic attachments in the two step AA was taken as 200 mm.

Resistance.

It was established experimentally that the height of the absorption volume in a single step instrument in the interval 200-600 mm has almost no effect on the resistance of the device. Therefore, in the subsequent experiments the resistance in a one step AA instrument was determined when the height of the absorption volume was 200 mm.

Experimental data on the resistance for different gas mass velocities as a function of the specific consumption of liquid per m^3 of gas (under normal conditions) is shown in figure 7. We can see from this figure that for gas-liquid flow in the AA absorber two hydraulic modes are observed and these are determined by the magnitude of liquid consumption. In the first mode, when the specific consumption of the liquid is not very large the resistance varies little when the consumption is increased. In the second mode with higher specific liquid consumption the resistance increases more rapidly.

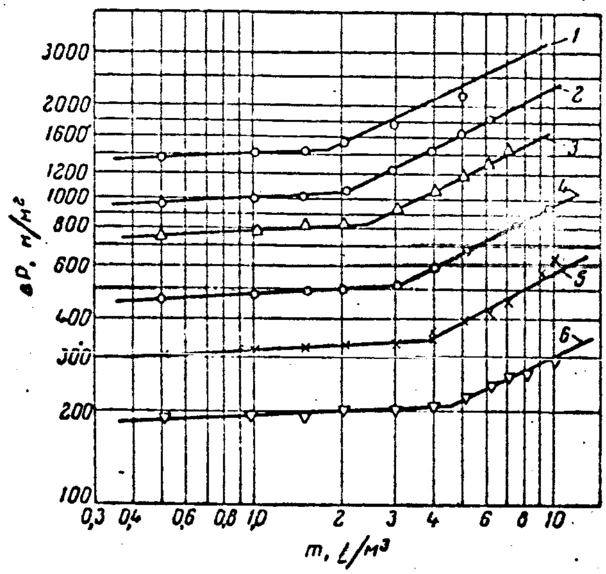

Figure 7. Variation in the resistance ΔP of a one step AA absorber as a function of the specific liquid consumption m and the gas mass velocity W_g:

Curve	W_g, kg/(m^2·sec)	L, l/hr
1	48.0	81.36
2	41.5	79.1
3	36.0	81.6
4	30.0	84.6
5	23.0	83.6
6	18.0	76.2

The transition from one mode to another is observed in the test equipment when the liquid consumption is approximately 80 liters per hour and is independent of the gas mass flow.

By processing the data the following equations have been established: for the first mode:

$$\frac{\Delta P}{\Delta P_s} = 1 + Am^{0.68} \qquad (14)$$

for the second mode:

$$\frac{\Delta P}{\Delta P_s} = 1 + A'm^{1.9} \qquad (15)$$

where A and A' are functions of the gas mass velocity.

The resistance to a single phase flow is given by the equation

$$\Delta P_s = \zeta \frac{W_g^2}{2\rho_g}. \qquad (16)$$

The resistance coefficient ζ for the test equipment is equal to 1.32.

Figure 8 shows the variation in the resistance of a two step instrument as a function of the specific liquid consumption m. By comparing figures 7 and 8 we can see that the resistance of a two stage device for all the test gas mass velocities and specific consumptions are approximately two times greater than for a single step device. The transition from one mode to another in a two step AA equipment takes place when the liquid consumption is the same as in a single step device. As the mass gas velocity increases the transition points are displaced in the direction of lower specific liquid consumptions.

Mass Transfer.

The results of the experiments on the mass transfer in the second mode[1], conducted with a single step AA instrument are given in figure 9 when the height of the absorption volume is 200 mm. This figure shows the variation in the number of transport units as a function of the specific liquid consumption. We can see from this figure that as the gas mass velocity increases and the spe- /131 cific consumption of the liquid increases, the number of transport units

[1]The number of experiments on mass transfer in the region of the first mode was small and the accuracy for the rather small specific liquid consumption was not very high; therefore, equations for this mode are not introduced.

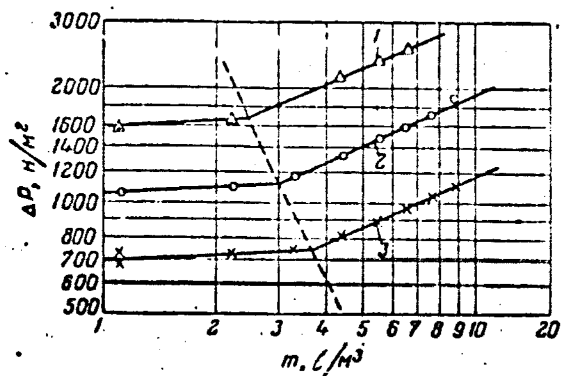

Figure 8. Variation in the resistance ΔP of a two step AA absorber as a function of the specific liquid consumption m and the gas mass velocity W_g:

Curve	W_g, kg/($m^2 \cdot$sec)	L, 1/hr
1	36	85.0
2	30	84.6
3	23	83.6

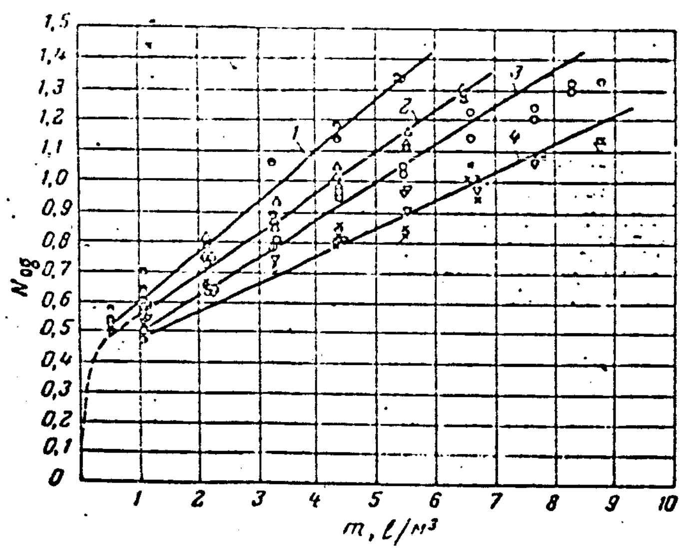

Figure 9. Variation in N_{0g} as a function of m in a single step AA absorber for different W_g: 1, W_g = 48 kg/($m^2 \cdot$sec); 2, W_g = 36; 3, W_g = 30; 4, W_g = 23 and 18.

increases. The variation in the number of transport units as a function of specific liquid consumption may be represented in the form

$$N_{og} = A + Bm \tag{17}$$

where A and B are functions of the mass gas flow.

The effect of the absorption volume height on the number of transport units is shown in figure 10. It can be seen from this figure that as the height of the absorption volume is increased, the number of transport units also increases. In the first approximation the variation in the number of transport units as a function of absorption volume height can be assumed to be linear

$$N_{og} = N_0 + bh \tag{18}$$

where b is a constant.

We can assume that the term N_0 characterizes the mass transfer at the instant of time when the spray is formed while the term bh characterizes the mass transfer in the absorption volume of the instrument. Then equation (18) becomes analogous to equation (4) for the Venturi tube without a jet orifice.

The data on mass transfer for a two-step AA instrument are shown on figure 11. In this drawing the broken lines give the experimental data on mass transfer for a single step instrument with h = 200 and h = 400 mm. As we can see from the drawing the number of transport units in the two step instrument for all the test gas mass velocities are 1.7 times higher than for the same values of W_g in a single step instrument when the height of the absorption volume is 200 mm.

If we compare data on the mass transfer in a single step instrument with h = 400 mm (the drawing shows only one curve for W_g = 23 kg/(m^2·sec)) with the corresponding data for the two step equipment it turns out that in the latter the number of transport units is 1.4 times greater.

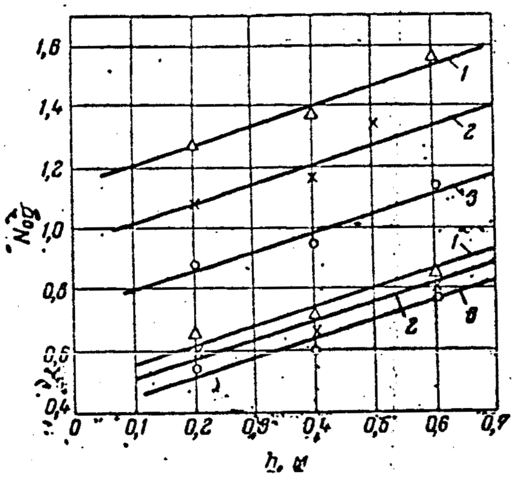

Figure 10. Variation in N_{og} as a function of the absorption volume height h in a single step AA absorber for different W_g (the upper curves m = 4.3 l/m^3; lower curves, m = 1.1 l/m^3): 1, W_g = 48 kg/(m^2·sec); 2, W_g = 36; 3, W_g = 23.

Thus, for the same common height of the absorption volume the installation of the second step increases the mass transfer. However, in this case the resistance of the instrument, as pointed out above, increases by a factor of 2. Therefore, the ratio $\Delta P/N_{og}$ for a two step instrument is higher than for a one step instrument.

Venturi Absorber with a Jet Orifice

The resistance of a Venturi absorber with a jet orifice and the mass transfer in it were investigated earlier (refs. 5-10). The purpose of the present investigation was to obtain experimental data necessary for a comparison of the three types of absorption instruments which are considered. /132

The installation setup and method of investigating the Venturi absorber with a jet orifice are the same as those used in experiments on the absorption of ammonia by water in the AA instrument.

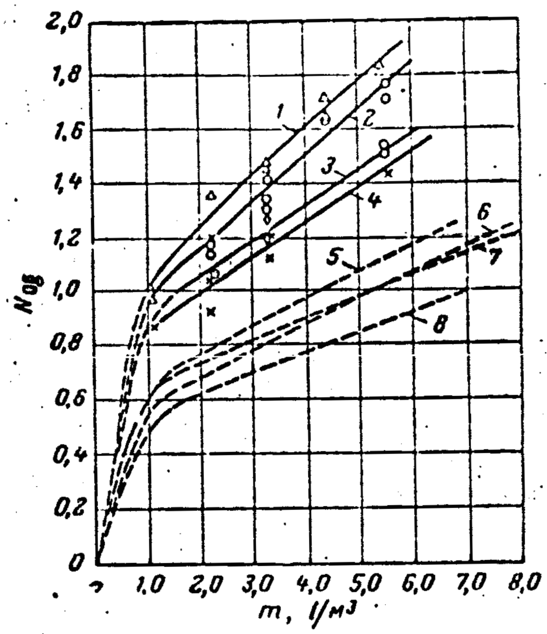

Figure 11. Variation in N_{og} as a function of m in a two step (curves 1-4) and in a one step (curves 5-8) of AA absorbers for different values of W_g and h:

Curve	W_g, kg/(m^2·sec)	h, mm
1	36	-
2	30	-
3	27	-
4	23	-
5	36	200
6	30	200
7	23	400
8	23	200

A Venturi tube with a throat diameter of 20 mm was machined; the cone angle of the diffuser was equal to 8^o. Water was introduced into the instrument by a centrifugal jet orifice with an opening diameter of 2 mm; the exposure angle of the jet without the air supply was $40\text{-}60^o$. The most rational position of the jet orifice along the height of the instrument was determined from preliminary experiments.

The data for the Venturi absorber with a jet orifice are shown in figures 12 and 13.

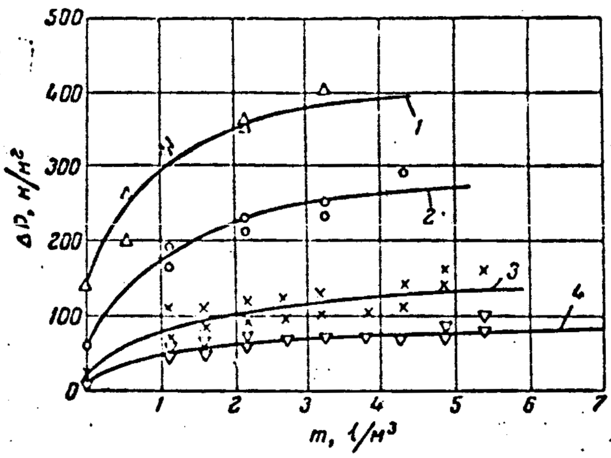

Figure 12. Variation in ΔP as a function of m for different values of W_g in the Venturi absorber with a jet orifice: 1, W_g = 36 kg/(m²·sec); 2, W_g = 30; 3, W_g = 23; 4, W_g = 18.

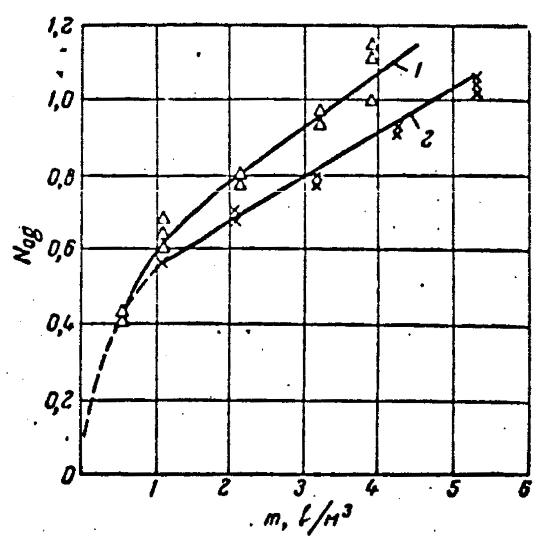

Figure 13. Variation in N_{og} as a function of m for different values of W_g in a Venturi absorber with a jet orifice: 1, W_g = 36 kg/(m²·sec); 2, W_g = 23.

The variation in the number of transport units as a function of the specific liquid consumption in the Venturi absorber with a jet orifice can be expressed by the equation

$$N_{og} = A + Bm \tag{19}$$

Equations (17) and (19) are analogous but the constants A and B have different values.

Comparison of the Test Absorbers

A comparison of the test absorbers (figs. 14-16) was carried out on the basis of the resistance of instruments ΔP, the number of transport units N_{og} and the specific resistance $\Delta P/N_{og}$ as a function of the specific liquid consumption m for gas mass velocities of 36 and 26 $kg/(m^2 \cdot sec)$.

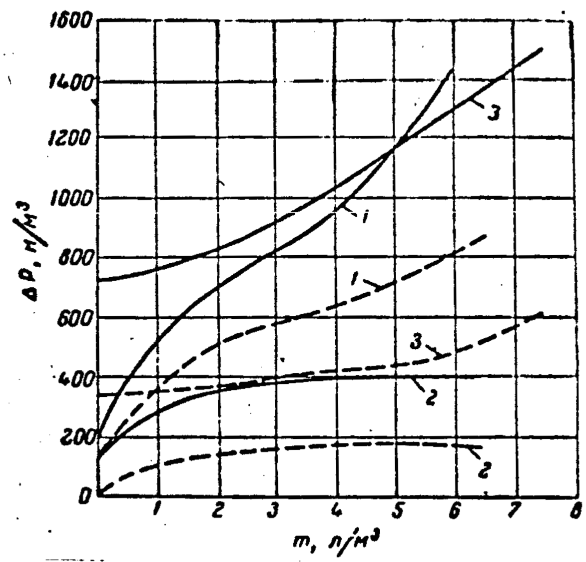

Figure 14. Comparative data on the resistance of 3 test absorbers (the solid lines are for W_g = 36 $kg/(m^2 \cdot sec)$; the broken lines are for W_g = 26 $kg/(m^2 \cdot sec)$): 1, Venturi absorber without a jet orifice; 2, Venturi absorber with a jet orifice; 3, AA absorber (h = 200 mm).

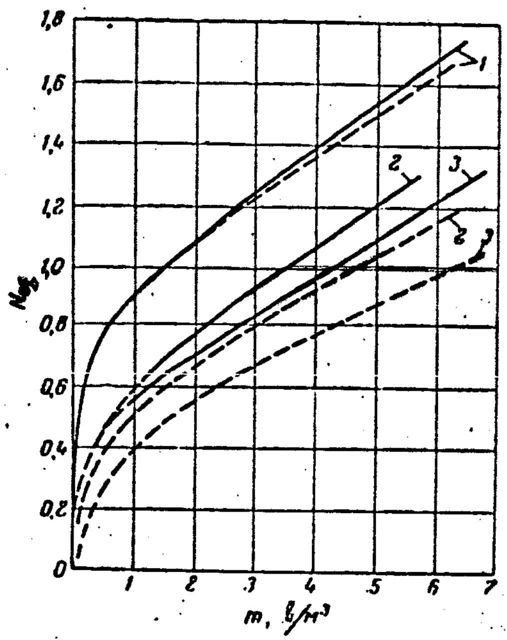

Figure 15. Comparative data on mass transport for three test absorbers (solid lines for $W_g = 36\ kg/(m^2 \cdot sec)$; broken lines for $W_g = 26\ kg/(m^2 \cdot sec)$): 1, Venturi absorber without a jet orifice; 2, Venturi absorber with a jet orifice; 3, AA absorber (h = 200 mm).

The results of comparisons show that the Venturi absorber with a jet orifice has the lowest hydraulic resistance in the investigated range of specific liquid consumption m; however, the number of transport units is lower for it than for the Venturi absorber without a jet orifice although somewhat higher than for the AA absorber. The Venturi absorber with a jet orifice has the lowest specific resistance. We should note that this absorber requires an additional expenditure of energy for the liquid supply and if the total consumption of the energy is considered, its advantage may turn out to be minimum. Cases are possible when from the point of view of total energy consumption its performance will be worse than that of the other types of absorbers tested by us.

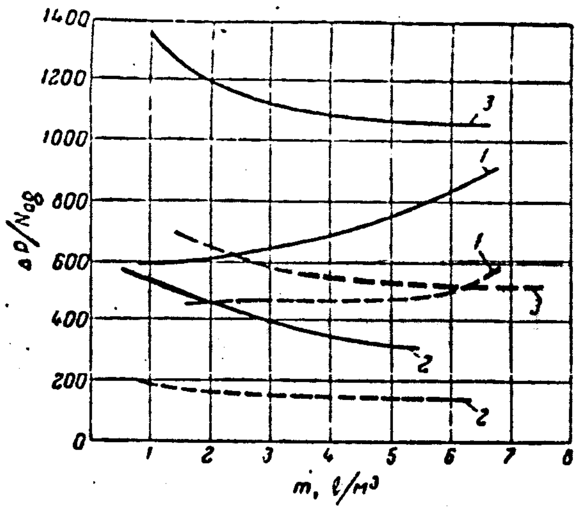

Figure 16. Comparative data on the specific resistance for three test absorbers (solid lines are for $W_g = 36$ kg/(m^2·sec); broken lines are for $W_g = 26$ kg/(m^2·sec)): 1, Venturi absorber without a jet orifice; 2, Venturi absorber with a jet orifice; 3, AA absorber (h = 200 mm).

By comparing the Venturi absorber without a jet orifice and the AA absorber we can state that when the specific liquid consumption is less than approximately 6 l/m^3, the first has a lower P/N_{og} ratio while for higher specific liquid consumptions the second has a lower ratio. The results of this comparison should be verified by using equipment of large size.

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